Addressing Test Challenges of 802.11ay Technology

Xiang Feng

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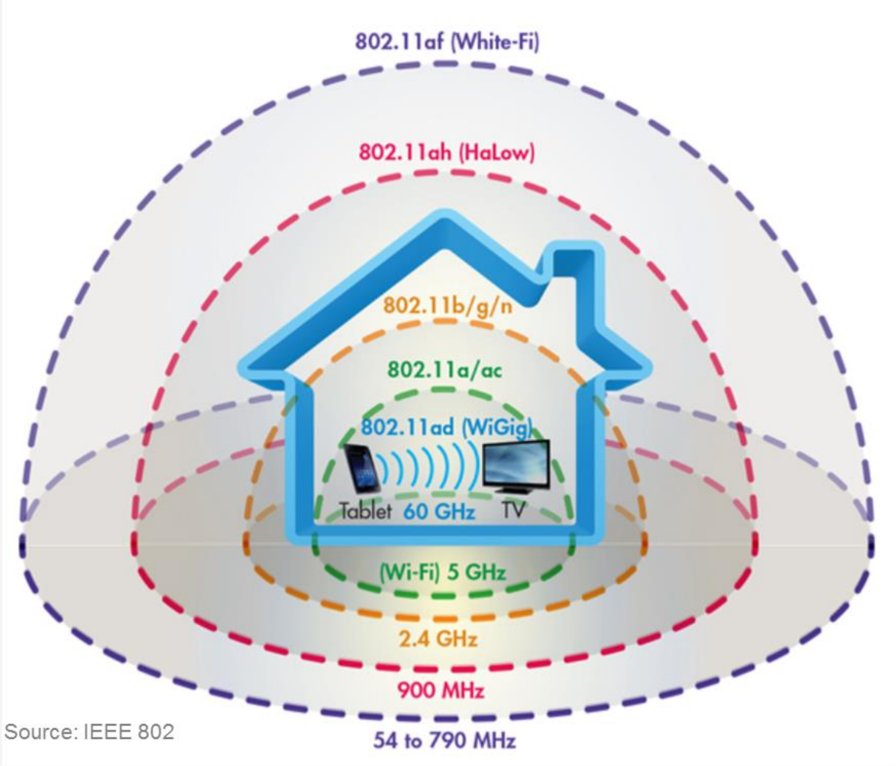
Keysight Technologies

Agenda

- WiFi/WiGig overview
- Key technologies of 802.11ad/ay
- Test Challenges
- R&D testbed applied to 802.11ay
- Summary

Evolution of WLAN Standards



Source: IEEE 802

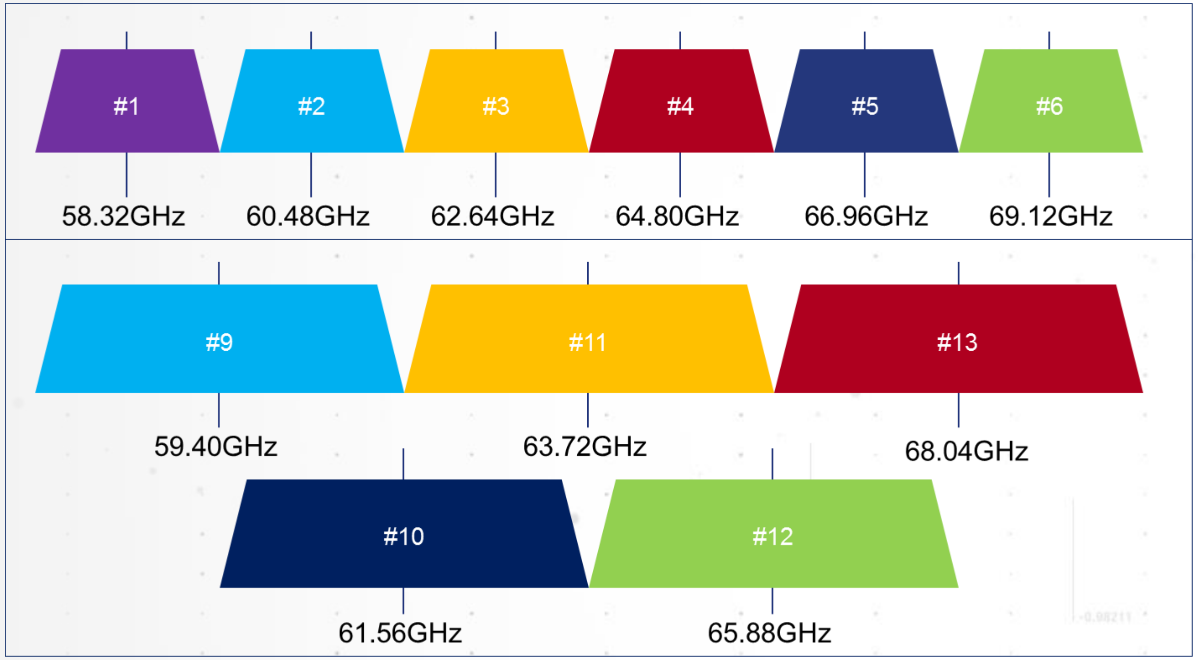
Standard	Frequency (GHz)	Bandwidth (MHz)	Modulation	Max Data Rate
802.11b	2.4	22	DSSS	11 Mbps
802.11a	5	20	OFDM	54 Mbps
802.11g	2.4	20	OFDM	54 Mbps
802.11n (WiFi 4)	2.4, 5	20, 40	MIMO-OFDM	600 Mbps
802.11ac (WiFi 5)	5	20,40,80,160	MIMO-OFDM	7 Gbps
802.11ax (WiFi 6)	2.4, 5, 6	20,40,80,160	MIMO-OFDM	10 Gbps
802.11ad	**60**	**2160**	**SC/QAM**	**~8 Gbps**
802.11ay	**60**	**(2160) x2, x3, x4**	**SC/QAM, MIMO-OFDM**	**>20 Gbps**

Note: Capacity is the key performance metric for Wi-Fi instead of theoretical peak rate.

- Generally uses unlicensed or license-exempt spectrum, with the exceptions of 11p and 11af
  - 2.4GHz/5GHz/Add 6 GHz band, extending operation to 7.125 GHz in March
  - 5 GHz: Dynamic Frequency Selection (DFS) and Transmit Power Control (TPC) capabilities always needed
  - 60GHz ISM band (WiGig)
  - 900MHz (802.11ah) for IoT

WiGig

60GHz: 802.11ad/ay



802.11ad and 802.11ay channels

Support of 2.16 GHz channels and channel bonding of two 2.16 GHz channels is mandatory for EDMG STA

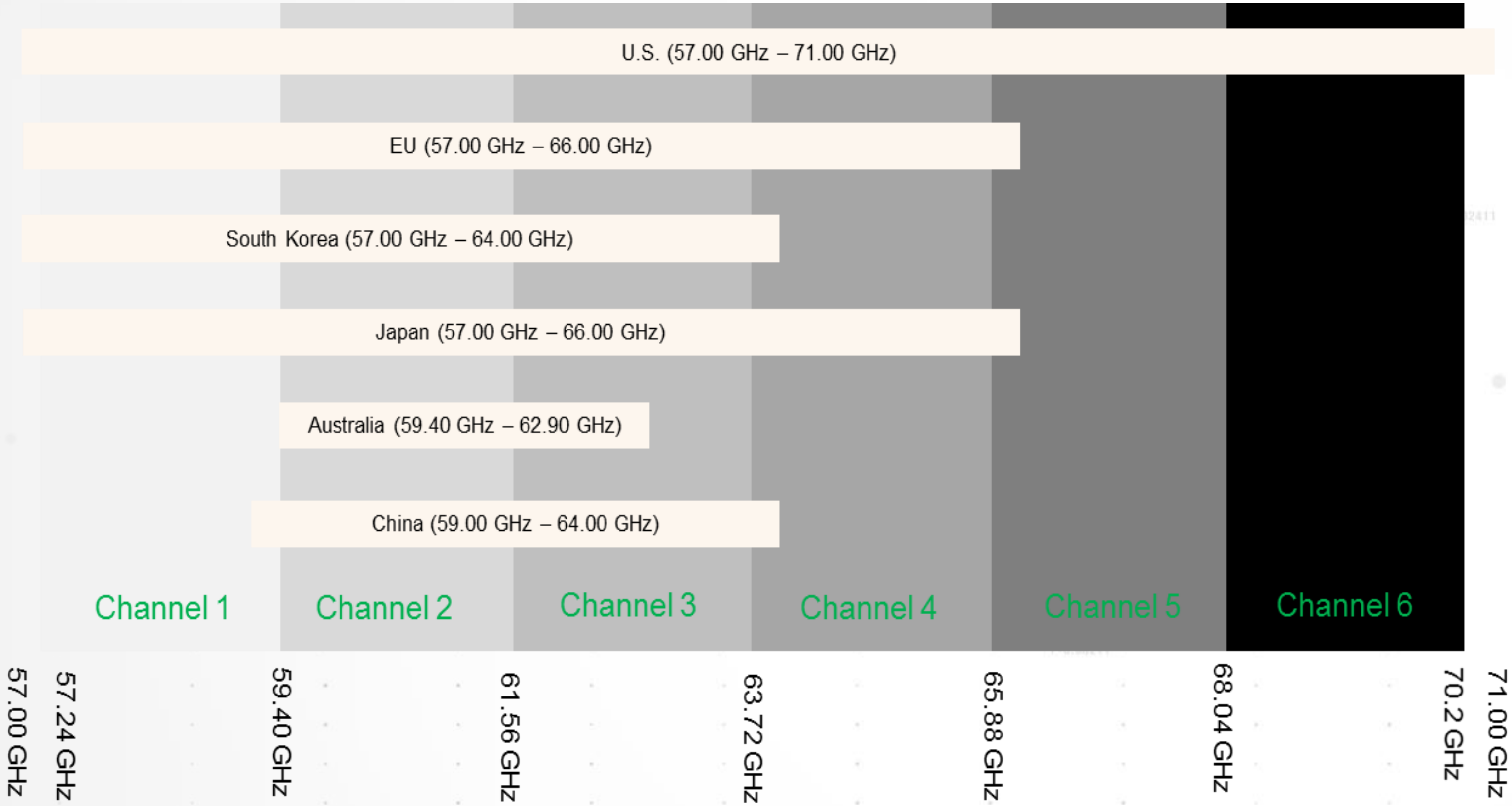
Channel aggregation and bonding of 3 or 4 2.16GHz channels is optional.

Using unlicensed spectrum at mmWave band

- 802.11ad, published in 2012, was the first of the new specific-use Wi-Fi standards, created to facilitate very-high-speed data transfer using the 60-GHz band.
  - DMG(Directional Multi-Gigabit) PHY
    - Bandwidth: 2.16GHz
    - Single Carrier: QAM (OFDM Obsoleted)
    - Beam Steering
- IEEE 802.11ay is the next-generation wireless standard at 60 GHz, an extension of the existing 11ad, aimed to extend the throughput, range and use-cases, and is expected to be completed in 2019. Draft 3.0 in Mar, 2019.
  - *Enables at least one mode of operation capable of supporting a maximum throughput of at least 20Gbps, while maintaining/improving the power efficiency.*
  - EDMG(Enhanced DMG) PHY, backward compatibility with 11ad, add support for space-time streams, DL MU transmissions and multiple channel widths.

(http://www.ieee802.org/11/Reports/tgay_update.htm)

WiGig Worldwide Spectrum



- Advantages of 60GHz band
  - Large spectrum
  - Small antenna size
  - Easy beamforming
  - Directional antennas for spatial reuse
  - Low interference
  - Inherent security
- Disadvantages of 60GHz band
  - Large attenuation and oxygen absorption
  - Directional deafness
  - Easily blocked

UK extended license exempt access up to 71GHz (from 57-66GHz)

Ref: WFA, Wi-Fi CERTIFIED WiGig Messaging Architecture v1.0

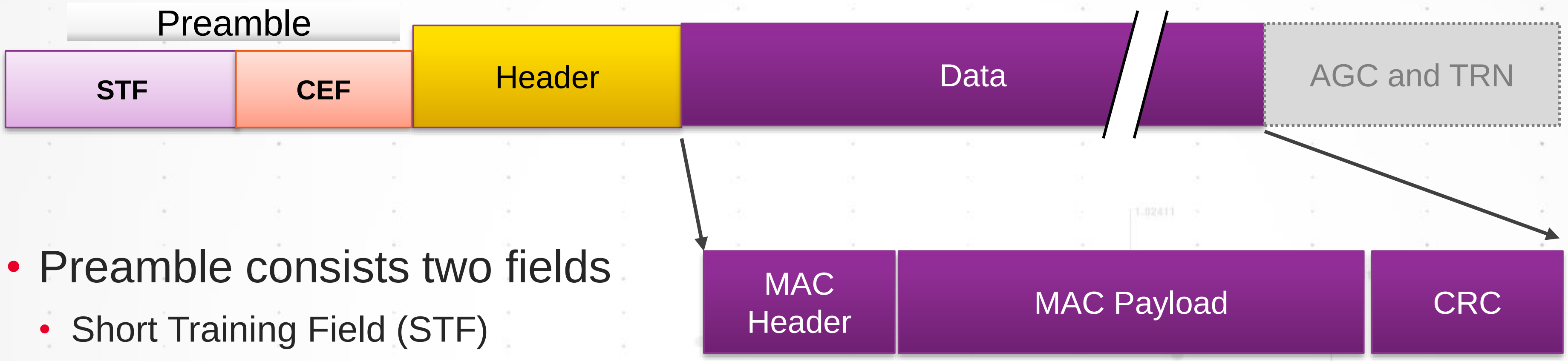
Directional transmission with large arrays provides necessary gain

802.11ad Overview

A backwards-compatible extension to the IEEE 802.11-2012 specification that adds a new MAC/PHY to provide short range, high capacity links in the 60 GHz unlicensed band.

- Single bandwidth: 2.16GHz
- PHY Modes
  - Control PHY: for low SNR prior to beamforming
  - Single Carrier (SC) PHY: efficient and low complexity
  - Low-power SC: for power deduction by RS encoder
  - OFDM PHY: for high performance and maximum data rate (obsoleted)
  - Share same packet Structure with common preamble, common LDPC structure
- Active antenna beam forming / steering (but not MIMO).
- MAC: Adapts 802.11 CSMA/CA mechanism, further adds a multi-MAC architecture suited to directional communication, also with combination of beamforming.

802.11ad Packet

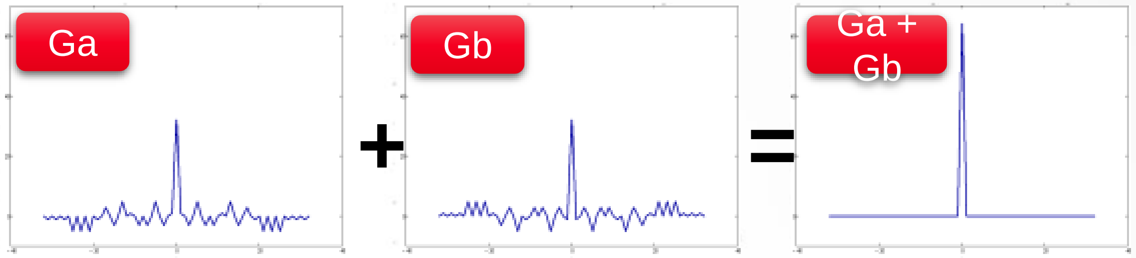


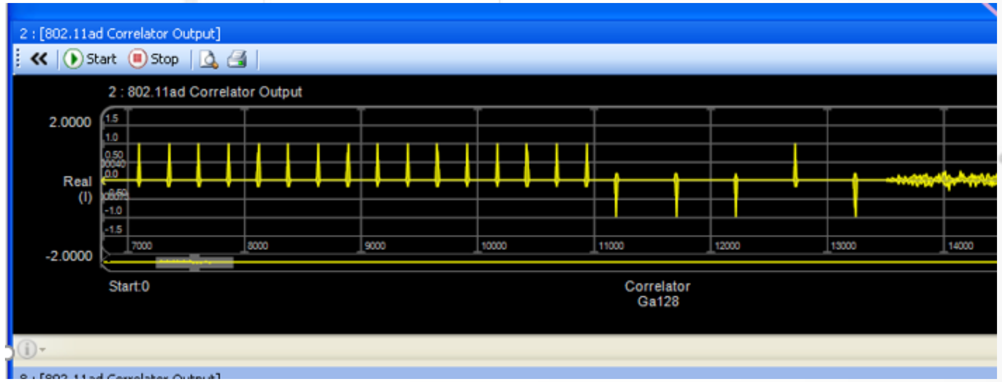
- Preamble consists two fields
  - Short Training Field (STF)
    - Timing estimation
    - AGC adjustment
  - Channel Estimation Field (CEF)
    - Channel estimation
- Header: include details of PPDU for demodulation
- Data: Payload data of PSDU
- Automatic Gain Control (AGC) and Training (TRN): Optional; for beamforming

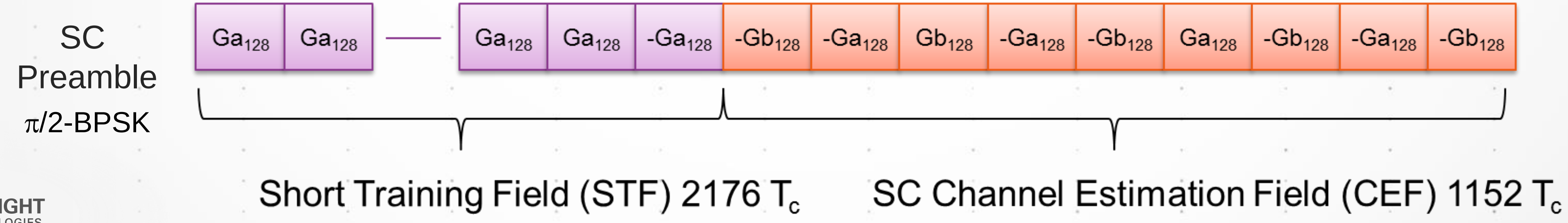
Golay Complementary Sequences

Pair of complementary sequences: Ga, Gb

- Used extensively in 802.11ad
  - Preamble
  - SC guard interval
  - Data Spreading
  - Beamforming training
  - AGC
- Important attributes of Golay sequences
  - Low side lobes and low DC content under π/2 rotation
  - Sum of G_a and G_b autocorrelations is perfect.
  - G_a and G_b autocorrelations can be performed in parallel using a single correlator.

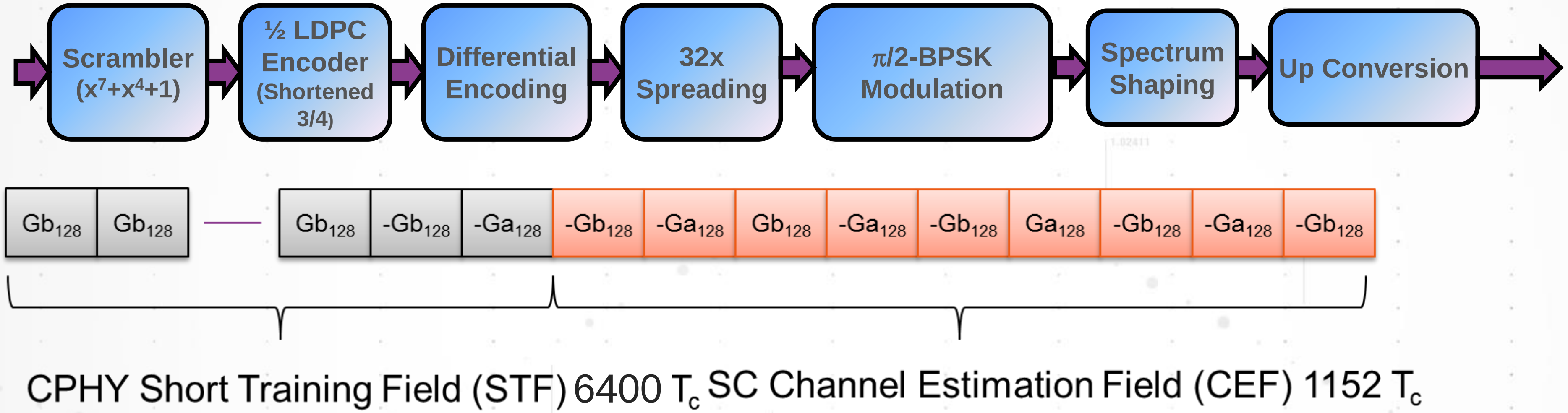






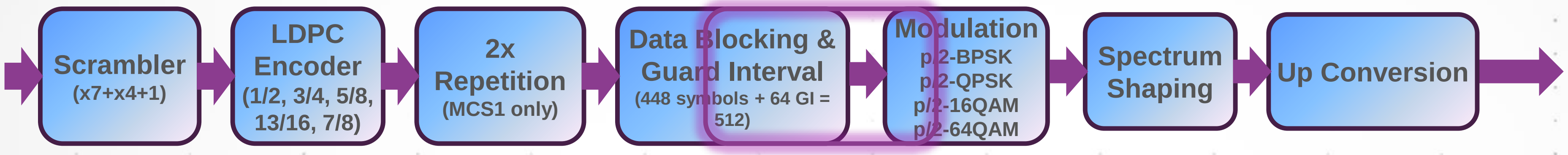
Control PHY (MCS0)

For management and control frames transmission: beacon, probe…

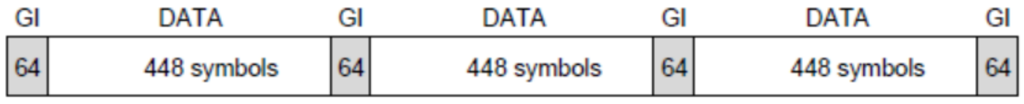


- Longer STF for robust discovery and detection
- CEF: 9 Golay sequences
- 32 sample Golay spreading sequence (~15dB processing gain)
- ½ LDPC encoding (from common rate ¾ LDPC code)
- π/2-DBPSK modulation
- Data Throughput = 27.5 Mbps [1.76 GSa/sec / 32x Spreading / 1/2 rate encoding]

SC PHY (MCS 1-12, 12.1-12.6)



- Variable coding rate and modulation depth
- All modulation types use π/2 rotation to reduce PAPR
- Guard interval: π/2-BPSK 64 point Golay sequence



- Symbol Rate = 1.76 GSym/sec
- Date rates up to ~8 Gbps
- Baseband filtering is not defined, however EVM is specified with a RRC filter

Control (CPHY)			
MCS	Coding	Modulation	Raw Bit Rate
0	1/2 LDPC, 32x Spreading	π/2-DBPSK	27.5 Mbps
Single Carrier (SCPHY)			
MCS	Coding	Modulation	Raw Bit Rate
1-12 12.1-12.6	1/2 LDPC, 2x repetition 1/2 LDPC, 5/8 LDPC 3/4 LDPC 13/16 LDPC 7/8 LDPC	π/2-BPSK, π/2-QPSK, π/2-16QAM π/2-64QAM	385 Mbps to ~8 Gbps
OFDM PHY (MCS 13~24: obsoleted)			
Low-Power Single Carrier (LPSCPHY)			
MCS	Coding	Modulation	Raw Bit Rate
25-31	RS(224,208) + Block Code(16/12/9/8,8)	π/2-BPSK, π/2-QPSK	625.6 Mbps to 2503 Mbps

Note: Low power SC is optional and provide lower processing power requirement

Summary of 802.11ad PHY

- PHY date rate: SC QAM, up to 8GHz with a range of MCSs.
- Channelization
  - 2.16GHz/channel
  - No channel bonding/aggregation
- Beamforming/steering
  - Supports multiple antennas, one at a time
  - Single stream
  - Supports channel feedback
  - Integrate with MAC schemes
- Transmission
  - Directional or quasi-omni-directional
  - All transmissions use the same channelization

802.11ay Overview

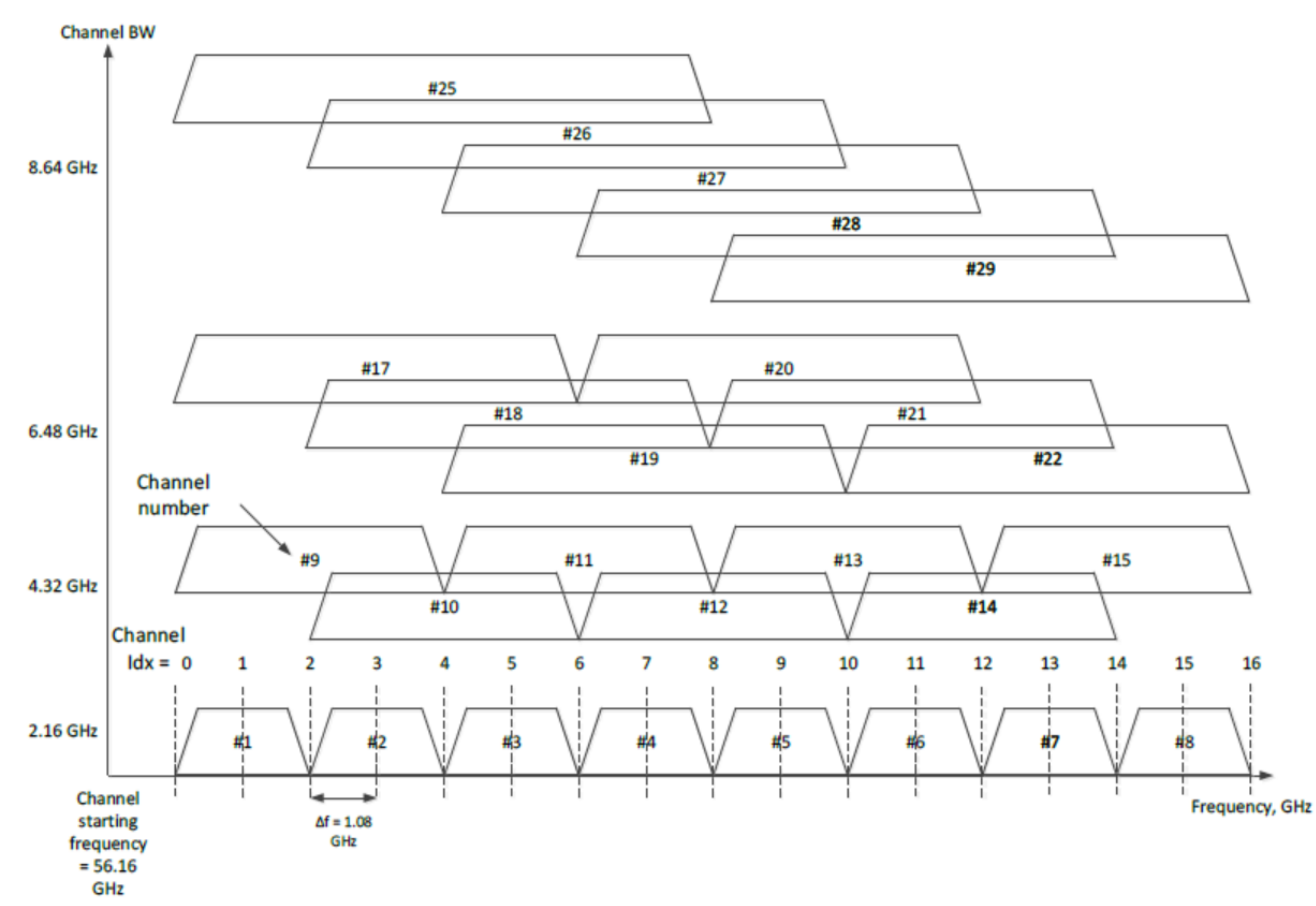
- 802.11ay is the follow-up of 802.11ad with
  - Higher throughput >100Gbps
  - Lower latency
  - Comparable or extended transmission distance
  - To meet the requirements of new applications
- Backward compatibility and coexistence with legacy directional multi-gigabit stations (802.11ad) operating in the same band.
- Timeline for Standardization

Mar 2015	May 2015 …	Jan 2017	Oct 2018	Feb 2019	Aug 2019	Mar 2020
Project Authorization Request approved	Initial Task Group meeting	Draft 0.1	Draft 2.1	D3.0	Ballot	Final 802 EC approval

802.11ay PHY Basic

- Features defined in standards
  - Multiple channel widths, up to 8GHz bandwidth
  - SC and OFDM modulations (up to 64QAM)
  - LDPC encoding (Short/long)
  - Space-time streams (STBC)
  - Downlink multi-user (MU)
  - MIMO/beamforming
- Mandatory features
  - EDMG format using SC modulation
  - 4.32GHz contiguous channel width
  - Single spatial stream in all supported channel widths
  - Non-EDMG duplicate format transmission of non-EDMG option of EDMG format preamble

802.11ay Channel



Single Channel/ bonding

- 2.16 GHz (N_{CB}=1)
- 4.32 GHz (N_{CB}=2)
- 6.46 GHz (N_{CB}=3)
- 8.64 GHz (N_{CB}=4)

Channel Aggregation (contiguous or non-contiguous)

- 2.16+2.16 GHz (N_{CB}=1)
- 4.32+4.32 GHz (N_{CB}=2)
- Primary + Secondary

Ref: IEEE P802.11ay/D3.0, Feb 2019

EDMG PPDU Packet

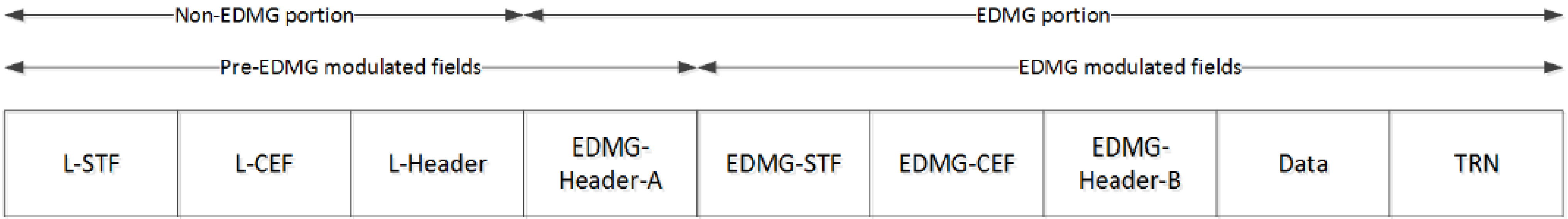


Figure 156 —EDMG PPDU format

Table 45—Fields of the EDMG PPDU

Field	Description
L-STF	Non-EDMG Short Training field
L-CEF	Non-EDMG Channel Estimation field
L-Header	Non-EDMG Header field
EDMG-Header-A	EDMG Header A field
EDMG-STF	EDMG Short Training field
EDMG-CEF	EDMG Channel Estimation field
EDMG-Header-B	EDMG Header B field
Data	The Data field carries the PSDU(s)
TRN	Training sequences field

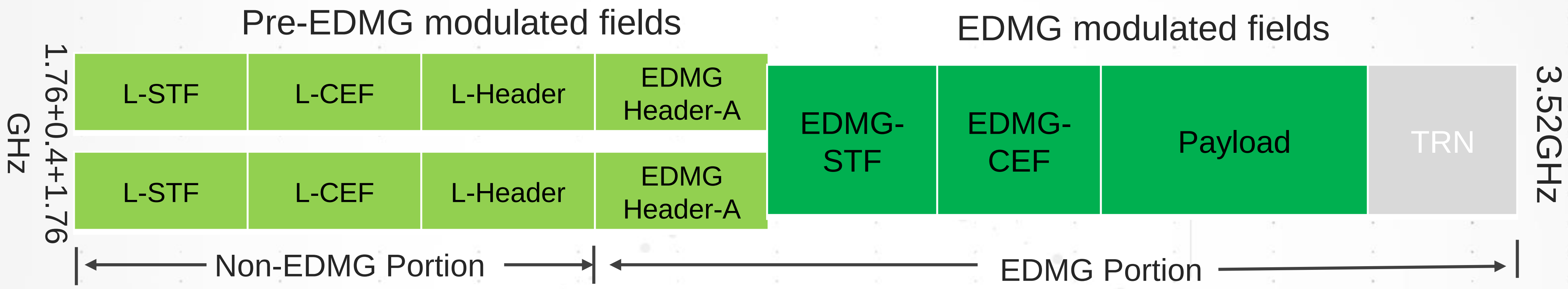
Ref: IEEE P802.11ay/D2.0, Jul 2018

The EDMG packet contains new fields necessary to support the additional capabilities, besides backward compatibility.

- A single packet structure for SC, OFDM, and control modes.
- Not all fields are transmitted in an EDMG PPDU, depending on whether the PPDU is an SU PPDU, an MU PPDU, or A-PPDU
  - EDMG-Header-B only transmitted in EDMG MU PPDU
  - TRN only for beamforming training and tracking

EDMG PPDU Packet

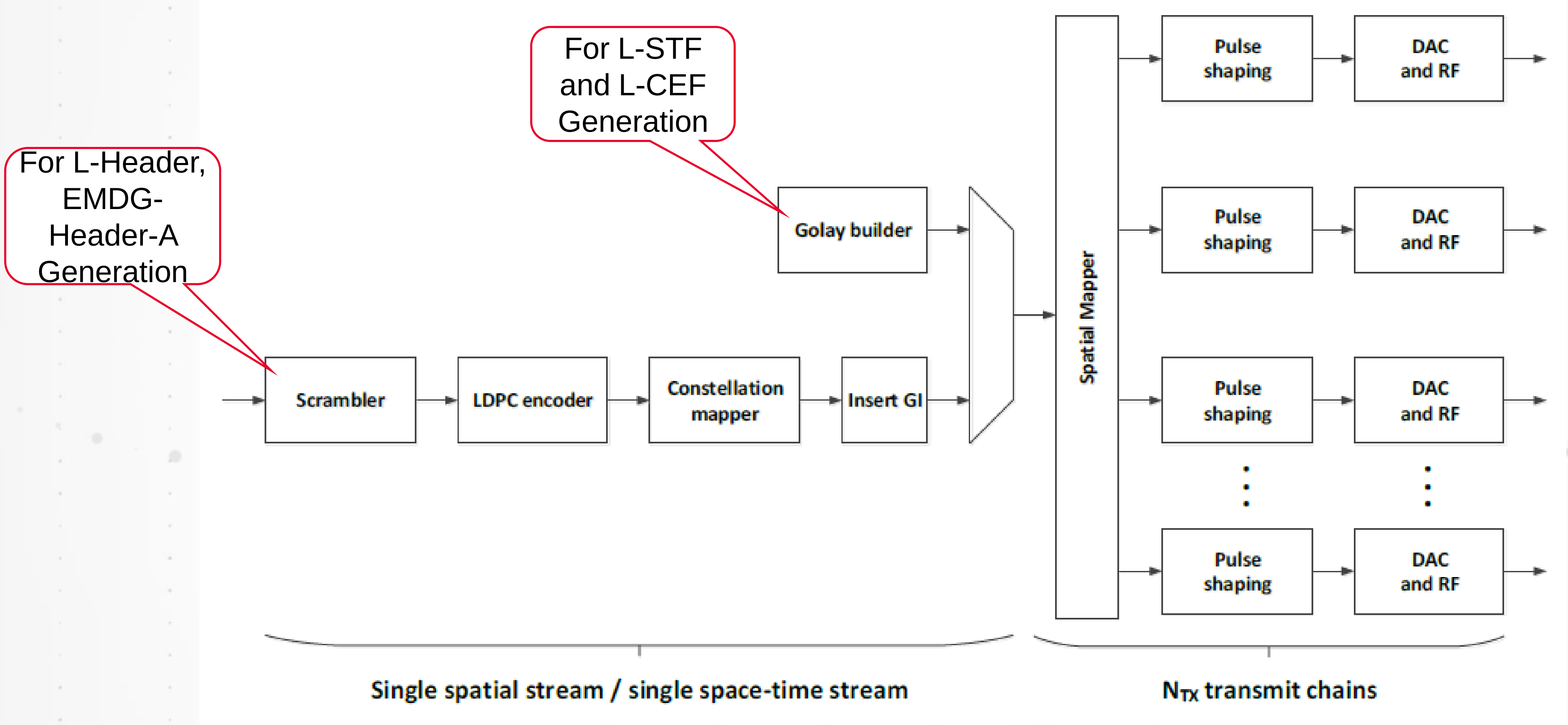
4.32GHz (N_{CB}=2)



- For non-EDMG and pre-EDMG modulated fields
  - SC chip rate: 1.76GHz
  - Using duplicate transmission over carriers of Fc +1.08GHz and Fc-1.08GHz
- For EDMG modulated fields
  - SC chip rate: 1.76GHz x N_{CB}
  - Center frequency: Fc

Transmitter Block Diagram

SC pre-EDMG modulated fields

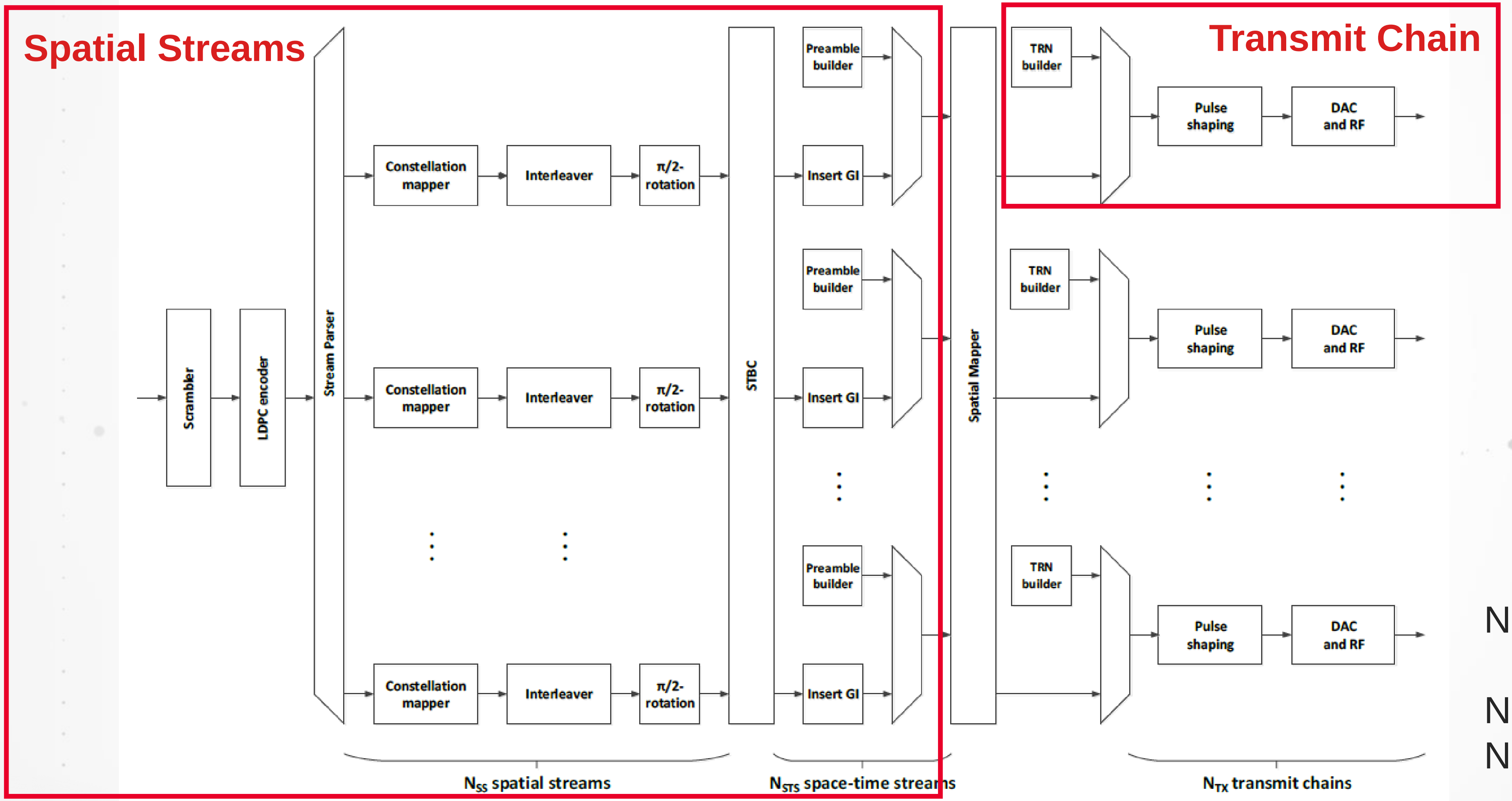


A single spatial stream mapped to N_{TX} transmit Chains with CSD

Ref: IEEE P802.11ay/D2.0, Jul 2018

Transmitter Block Diagram

SC/SU EDMG Modulated fields



N_{SS} <=8

$N_{STS}=2N_{SS}$

$N_{STS}<=N_{TX}$

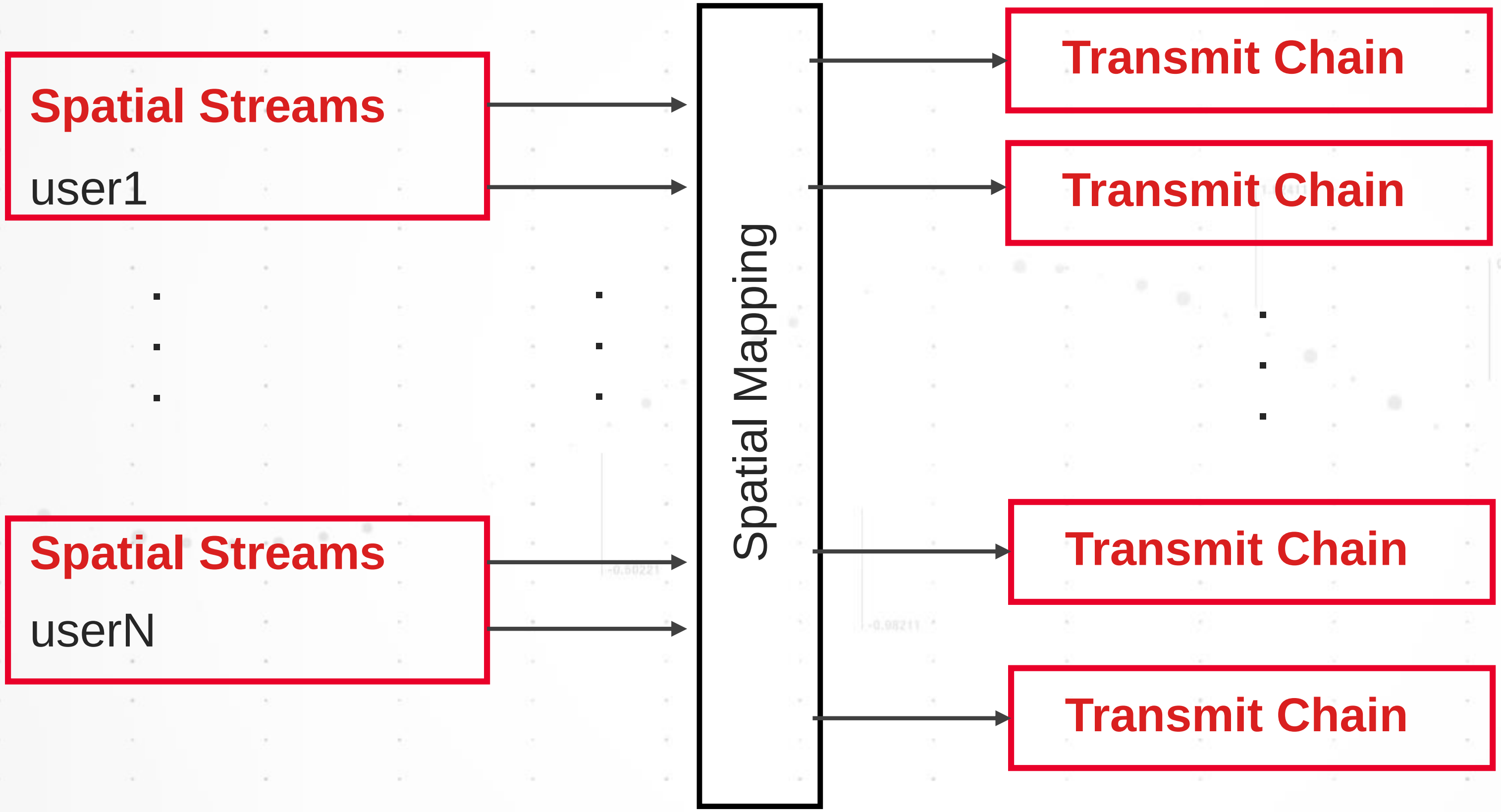
Ref: IEEE P802.11ay/D2.0, Jul 2018

Transmitter Block Diagram Description

- Scrambler: scrambles the data to reduce the probability of long sequences of 0s and 1s.
- LDPC encoder: enable error correction
- Stream parser: divides the encoded data into the groups of bits (spatial streams)
- Constellation mapper and pi/2-rotation: map the bits in each spatial stream to constellation points
- Interleaver: interleaving inside a SC symbol block
- STBC: spreads the modulated symbols from N_{SS} spatial streams in to N_{STS} space-time streams using a space-time block code. N_{STS} = 2x N_{SS}
- GI insertion: prepends the SC symbol block with guard interval defined as a pi/2-BPSK modulated Golay sequence
- Preamble builder: for pi/2-BPSK modulated Golay sequences comprising the EDMG-STF abd EDMG-CEF fields
- Spatial mapper: maps space-time streams to transmit chains
- Cyclic shift diversity (CSD): prevents the signal from unintentional beamforming for the duplicate PPDU transmission
- Phase shaping: with shape filter, which is implementation specific.

Transmitter Block Diagram

SC/Downlink MU



Up to 8 stations

N_{STS} total number of space-time streams

N_{TX} total number of transmit chains

MCS for SC

Table 81 —EDMG-MCSs for the EDMG SC mode

EDMG-MCS index	Modulation	N_{CBPS}	Repetition	Code Rate	Data rate per spatial stream (Mbps)		
					Normal GI	Short GI	Long GI
1	π/2-BPSK	1	2	1/2	N_{CB}×385.00	N_{CB}×412.50	N_{CB}×330.00
2	π/2-BPSK	1	1	1/2	N_{CB}×770.00	N_{CB}×825.00	N_{CB}×660.00
3	π/2-BPSK	1	1	5/8	N_{CB}×962.50	N_{CB}×1031.25	N_{CB}×825.00
4	π/2-BPSK	1	1	3/4	N_{CB}×1155.00	N_{CB}×1237.50	N_{CB}×990.00
5	π/2-BPSK	1	1	13/16	N_{CB}×1251.25	N_{CB}×1340.63	N_{CB}×1072.50
6	π/2-BPSK	1	1	7/8	N_{CB}×1347.50	N_{CB}×1443.75	N_{CB}×1155.00
7	π/2-QPSK	2	1	1/2	N_{CB}×1540.00	N_{CB}×1650.00	N_{CB}×1320.00
8	π/2-QPSK	2	1	5/8	N_{CB}×1925.00	N_{CB}×2062.50	N_{CB}×1650.00
9	π/2-QPSK	2	1	3/4	N_{CB}×2310.00	N_{CB}×2475.00	N_{CB}×1980.00
10	π/2-QPSK	2	1	13/16	N_{CB}×2502.50	N_{CB}×2681.25	N_{CB}×2145.00
11	π/2-QPSK	2	1	7/8	N_{CB}×2695.00	N_{CB}×2887.50	N_{CB}×2310.00
12	π/2-16-QAM	4	1	1/2	N_{CB}×3080.00	N_{CB}×3300.00	N_{CB}×2640.00
13	π/2-16-QAM	4	1	5/8	N_{CB}×3850.00	N_{CB}×4125.00	N_{CB}×3300.00
14	π/2-16-QAM	4	1	3/4	N_{CB}×4620.00	N_{CB}×4950.00	N_{CB}×3960.00
15	π/2-16-QAM	4	1	13/16	N_{CB}×5005.00	N_{CB}×5362.50	N_{CB}×4290.00
16	π/2-16-QAM	4	1	7/8	N_{CB}×5390.00	N_{CB}×5775.00	N_{CB}×4620.00
17	π/2-64-QAM	6	1	1/2	N_{CB}×4620.00	N_{CB}×4950.00	N_{CB}×3960.00
18	π/2-64-QAM	6	1	5/8	N_{CB}×5775.00	N_{CB}×6187.50	N_{CB}×4950.00
19	π/2-64-QAM	6	1	3/4	N_{CB}×6930.00	N_{CB}×7425.00	N_{CB}×5940.00
20	π/2-64-QAM	6	1	13/16	N_{CB}×7507.50	N_{CB}×8043.75	N_{CB}×6435.00
21	π/2-64-QAM	6	1	7/8	N_{CB}×8085.00	N_{CB}×8662.50	N_{CB}×6930.00

Note: Control mode (MCS 0) enables low SNR operation prior to beamforming with BPSK and a spreading factor of 32.

Ref: IEEE P802.11ay/D2.0, Jul 2018

- MCS value is carried in the EDMG-Header-A and –B fields.
- Data rate depends on GI, spatial streams and bandwidth.
  - 3 GI types: short (32x N_{CB}), normal, (64x N_{CB}), long(128x N_{CB}) and block size is 512 x N_{CB} symbols.
  - Total data rate is the sum of Data rate per SS.
  - So max data rate can be >200Gbps (Nss = 8 max)
- MCS 1-5 and 7-10 are mandatory.
- 8-PSK, NUC and DCM would be used depends on field setting.

MCS for SC

8PSK, NUC, DCM

Table 82 —EDMG-MCSs 12 and 13 for the EDMG SC mode if the π/2-8-PSK Applied field is 1

EDMG-MCS index	Modulation	N_{CBPS}	Repetition	Code Rate	Data rate per spatial stream (Mbps)		
					Normal GI	Short GI	Long GI
12	π/2-8-PSK	3	1	2/3	N_{CB}×3080.00	N_{CB}×3300.00	N_{CB}×2640.00
13	π/2-8-PSK	3	1	5/6	N_{CB}×3850.00	N_{CB}×4125.00	N_{CB}×3300.00

Table 83 —EDMG-MCSs 17 – 21 for the EDMG SC mode if the π/2-64-NUC Applied field is 1

EDMG-MCS index	Modulation	N_{CBPS}	Repetition	Code Rate	Data rate per spatial stream (Mbps)		
					Normal GI	Short GI	Long GI
17	π/2-64-NUC	6	1	1/2	N_{CB}×4620.00	N_{CB}×4950.00	N_{CB}×3960.00
18	π/2-64-NUC	6	1	5/8	N_{CB}×5775.00	N_{CB}×6187.50	N_{CB}×4950.00
19	π/2-64-NUC	6	1	3/4	N_{CB}×6930.00	N_{CB}×7425.00	N_{CB}×5940.00
20	π/2-64-NUC	6	1	13/16	N_{CB}×7507.50	N_{CB}×8043.75	N_{CB}×6435.00
21	π/2-64-NUC	6	1	7/8	N_{CB}×8085.00	N_{CB}×8662.50	N_{CB}×6930.00

Table 84 —EDMG-MCSs 2 – 6 for the EDMG SC mode if the DCM BPSK Applied field is 1

EDMG-MCS index	Modulation	N_{CBPS}	Repetition	Code Rate	Data rate per spatial stream (Mbps)		
					Normal GI	Short GI	Long GI
2	DCM π/2-BPSK	1	1	1/2	N_{CB}×770.00	N_{CB}×825.00	N_{CB}×660.00
3	DCM π/2-BPSK	1	1	5/8	N_{CB}×962.50	N_{CB}×1031.25	N_{CB}×825.00
4	DCM π/2-BPSK	1	1	3/4	N_{CB}×1155.00	N_{CB}×1237.50	N_{CB}×990.00
5	DCM π/2-BPSK	1	1	13/16	N_{CB}×1251.25	N_{CB}×1340.63	N_{CB}×1072.50
6	DCM π/2-BPSK	1	1	7/8	N_{CB}×1347.50	N_{CB}×1443.75	N_{CB}×1155.00

- New modulation schemes in 11ay, but optional
- 8PSK:
- NUC(non-uniform constellation): Reduce the gap to Shannon limit by optimizing the constellation with means of signal geometrical shaping for a specific SNR and channel model.
- DCM(Dual Carrier Modulation): for two channel aggregation mode for frequency domain diversity

Ref: IEEE P802.11ay/D2.0, Jul 2018

OFDM Mode (optional)

Achieve higher data rate

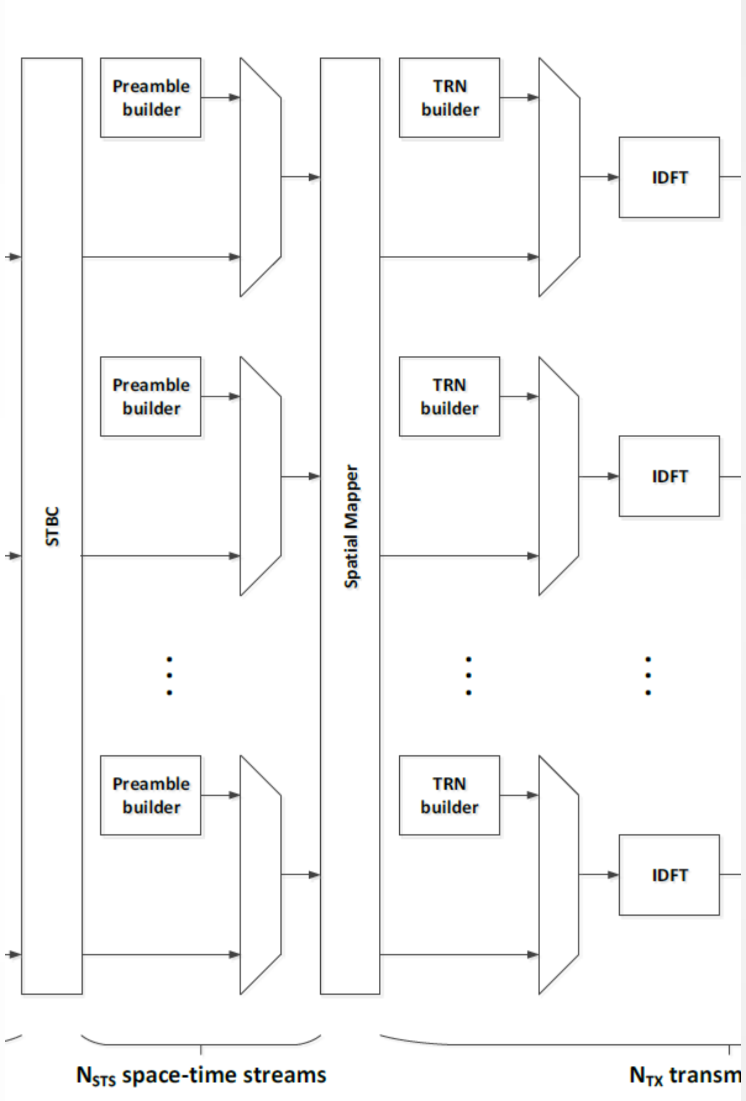
- Sample Rate Fs = 2.64xN_{CB} GHz
  - For Pre-EDMG modulated fields at SC chip rate 1.76GHz, the resampling procedure is applied with 3/2 sample rate conversion ratio to achieve 2.64GHz.
  - Subcarrier frequency space: 5.15625MHz
- DFT size: 512x N_{CB}
- Subcarrier number: data + Pilot + DC subcarriers
- Guard Interval and Windowing: prepends the OFDM symbol as a cycle extension of the OFDM symbol in time domain and applies a window function
- Frequency domain sequences for EDMG-STF/CEF

MIMO

Spatial mapping

N_{STS} space-time streams to N_{TX} transmit chains mapping with a spatial mapping matrix Q [N_{TX} X N_{STS}] or CSD. 4 basic mappings

- Direct mapping, $N_{STS} = N_{TX.}$ Q is identity matrix or exponential matrix
- Indirect mapping, $N_{STS} = N_{TX.}$ Q is a Normalized square matrix
  - Discrete Fourier matrix
  - Hadamard matrix
  - Direct mapping diagonal matrix with permutated row/columns
- Digital beamforming, $N_{STS} <= N_{TX.}$ Q is a rectangular matrix composed of complex values based on some knowledge of the channel
- Spatial expansion, $N_{STS} = 1 < N_{TX,}$ performed by application of CSD over different transmit chains.



Ref: IEEE P802.11ay/D2.0, Jul 2018

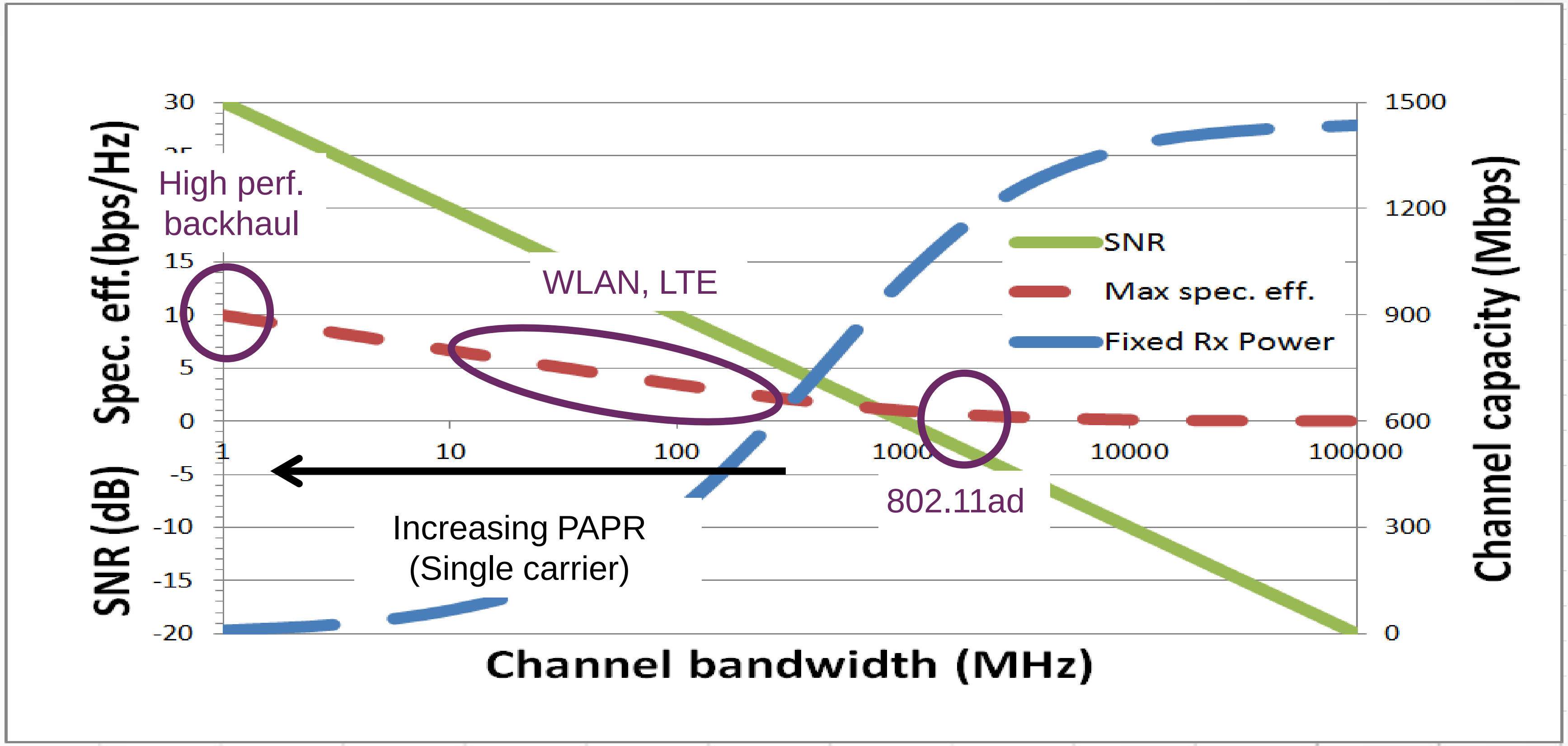
Summary of 11ay PHY

	802.11ad	802.11ay
PHY Modes	• SC QAM, up to 8GHz	• SC QAM, up to 8GHz/2.16GHz channel/stream • 8PSK, DCM, NUC (optional) • OFDM (optional)
Channelization	• 2.16GHz/channel • No channel bonding/aggregation	• 2.16GHz, 4.32, 6.48, 8.64GHz /channel • Support channel aggregation: 2.16+2.16GHz, 4.32+4.32GHz

Beamforming/steering	• Supports multiple antennas, one at a time
	• Single stream
	• Supports channel feedback
		• MIMO
		    • Multiple streams
		    • Multiple transmit chain
		    • Multiple antennas
		• Downlink Multi-user
		• Enhancement beamforming

Transmission/channel access	• Directional / quasi-omni before link established • All transmissions use the same channelization	• Directional / quasi-omni before link established • Multi-channel operation • Spatial division multiple access

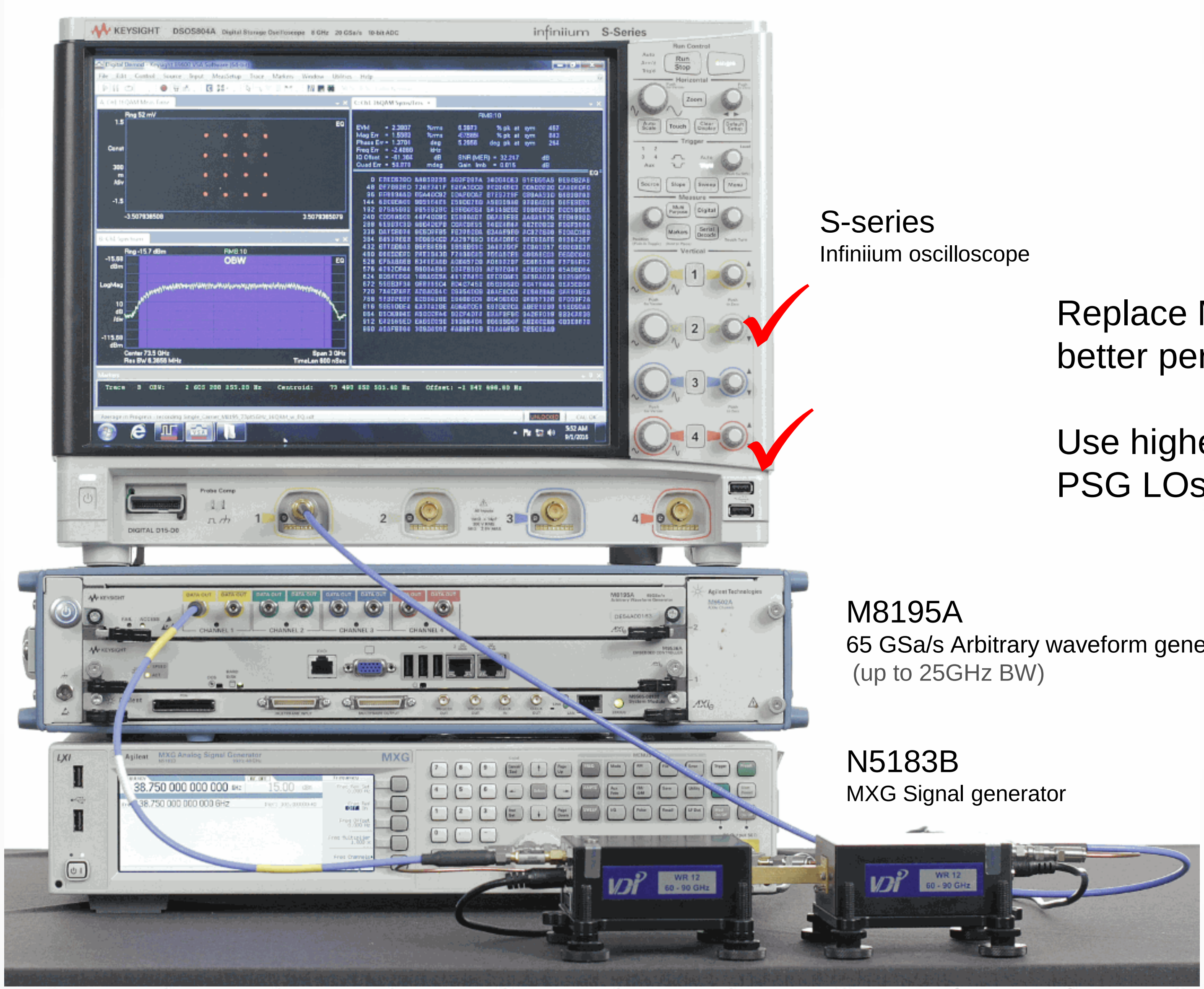
Higher Frequencies = Wider Bandwidth?



Some System Challenges with Higher Frequencies and Wider Bandwidths:

- Optimizing SNR
- Optimizing System Performance
  - Phase Noise
  - Linear Impairments (e.g. Amplitude and Phase vs. Frequency)
  - Nonlinear Impairments (e.g. Power Amplifier Gain Compression, Mixers, etc…)

New R&D Testbed for Emerging Millimeter-Wave Applications



S-series
Infiniium oscilloscope

Replace MXG LOs with PSG LOs for better performance

Use higher-performance oscilloscope and PSG LOs for best performance

M8195A
65 GSa/s Arbitrary waveform generator
(up to 25GHz BW)

N5183B
MXG Signal generator

V-band converters
(E-band are shown here)

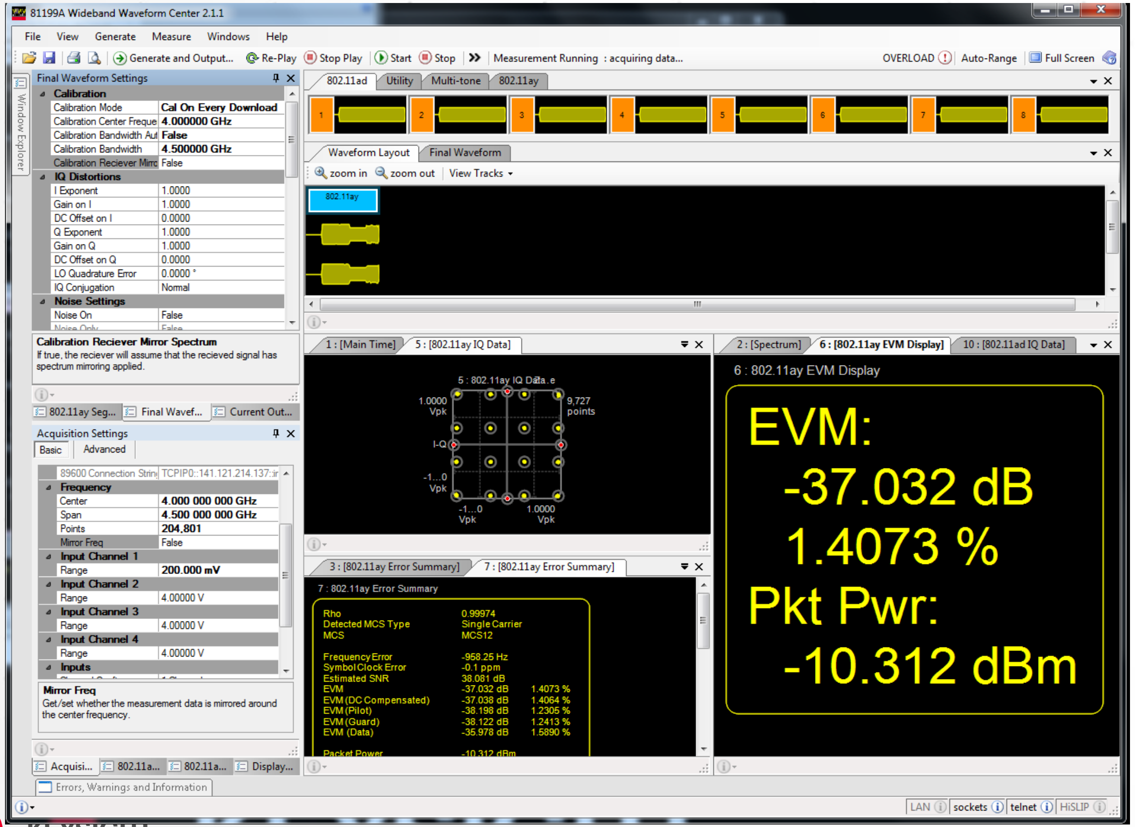
New R&D Testbed: M8195A AWG as a Wideband 802.11ay IF Source

M8195A AWG —4 GHz→ 33 GHz Scope

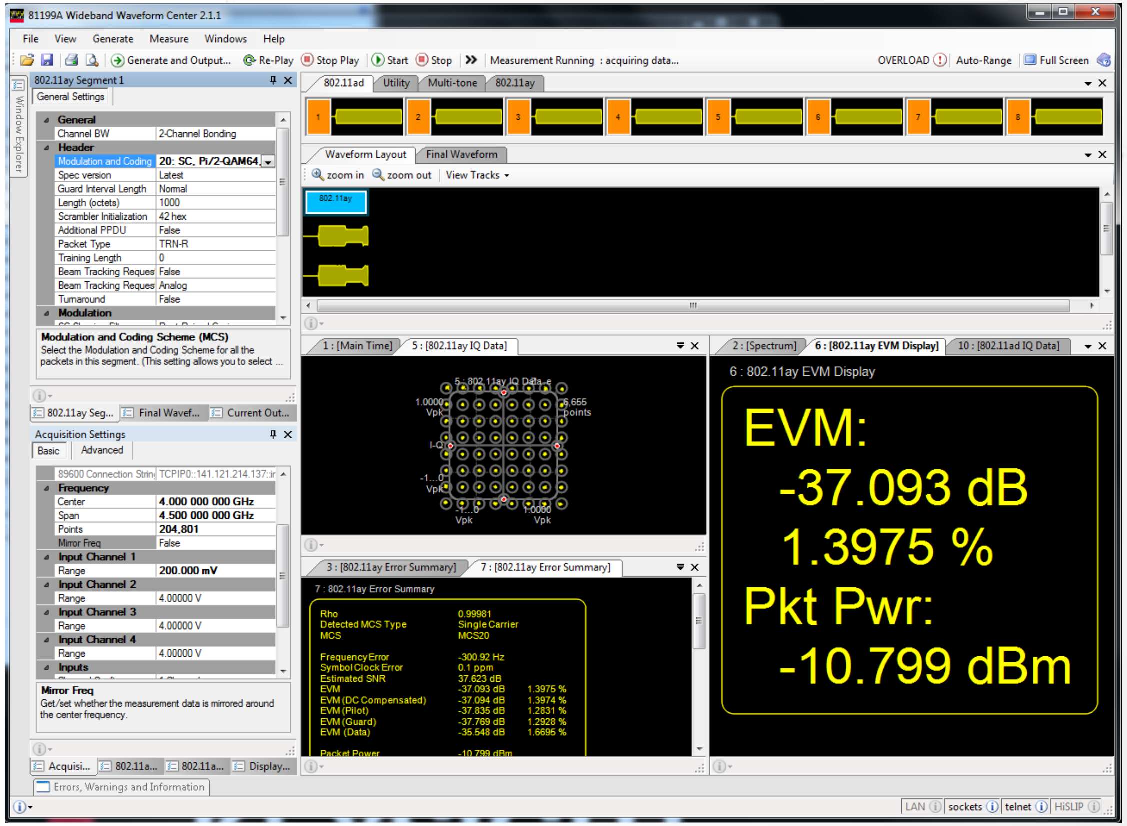
802.11ay MCS 12
-37.03 dB (1.41%) with WWC cal

802.11ay MCS 20
-37.09 dB (1.39%) with WWC cal

MCS 12, 4GHz IF M8195→ 33 GHz Scope, WWC Cal

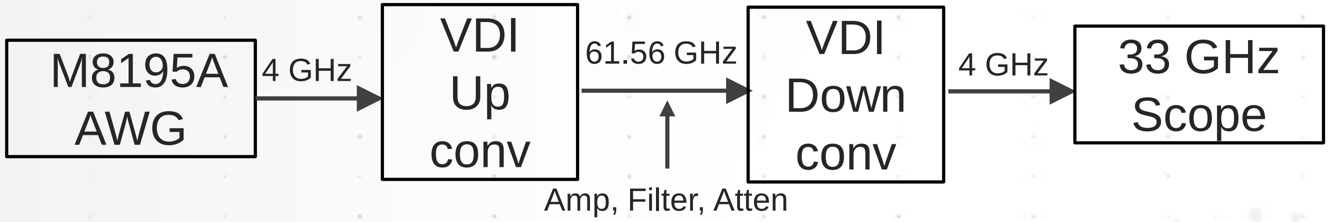


MCS 20, 4GHz IF M8195→ 33 GHz Scope, WWC Cal



KEYSIGHT TECHNOLOGIES

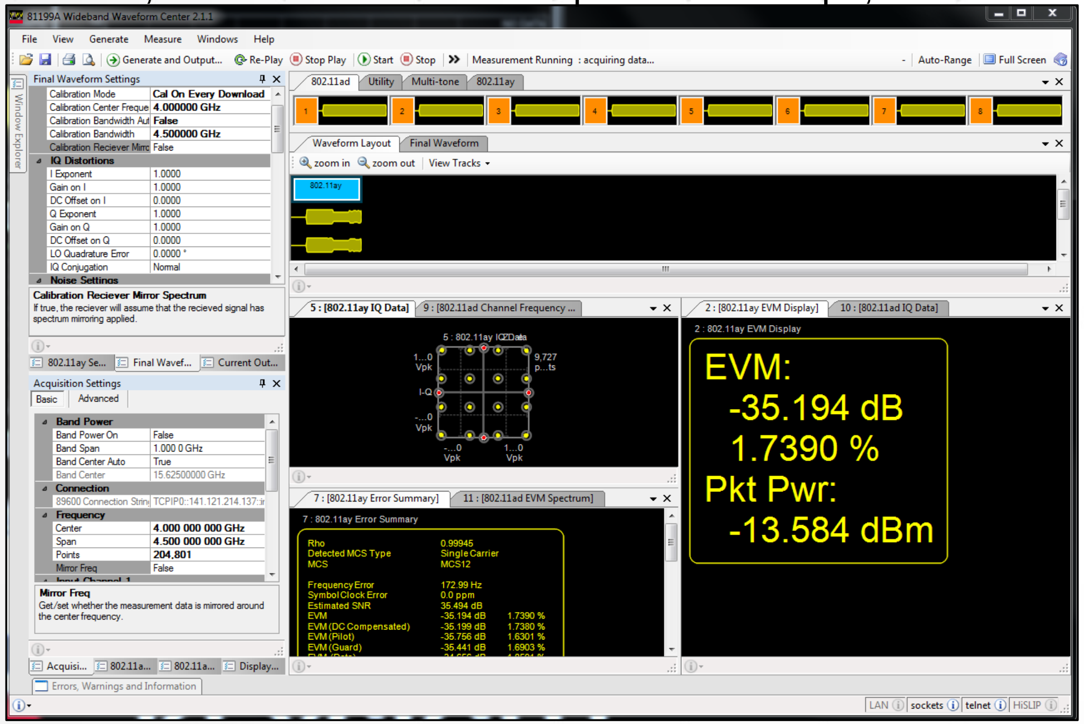
New R&D Testbed: 802.11ay mmWave Performance, with WWC Calibration (4 GHz-> 61.56 GHz->4 GHz)



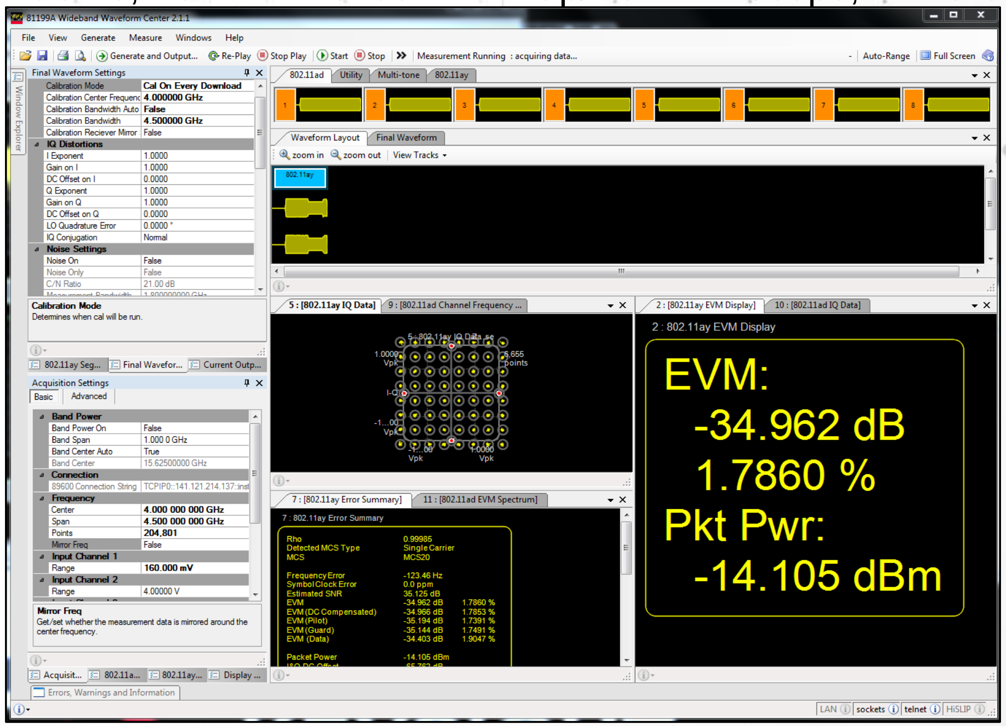
MCS 12
-35.19 dB (1.74%) with WWC cal

MCS 20
-34.96 dB (1.78%) with WWC cal

MCS 12, 4GHz IF M8195→ VDI Up/Down → Scope, WWC Cal



MCS 20, 4GHz IF M8195→ VDI Up/Down → Scope, WWC Cal



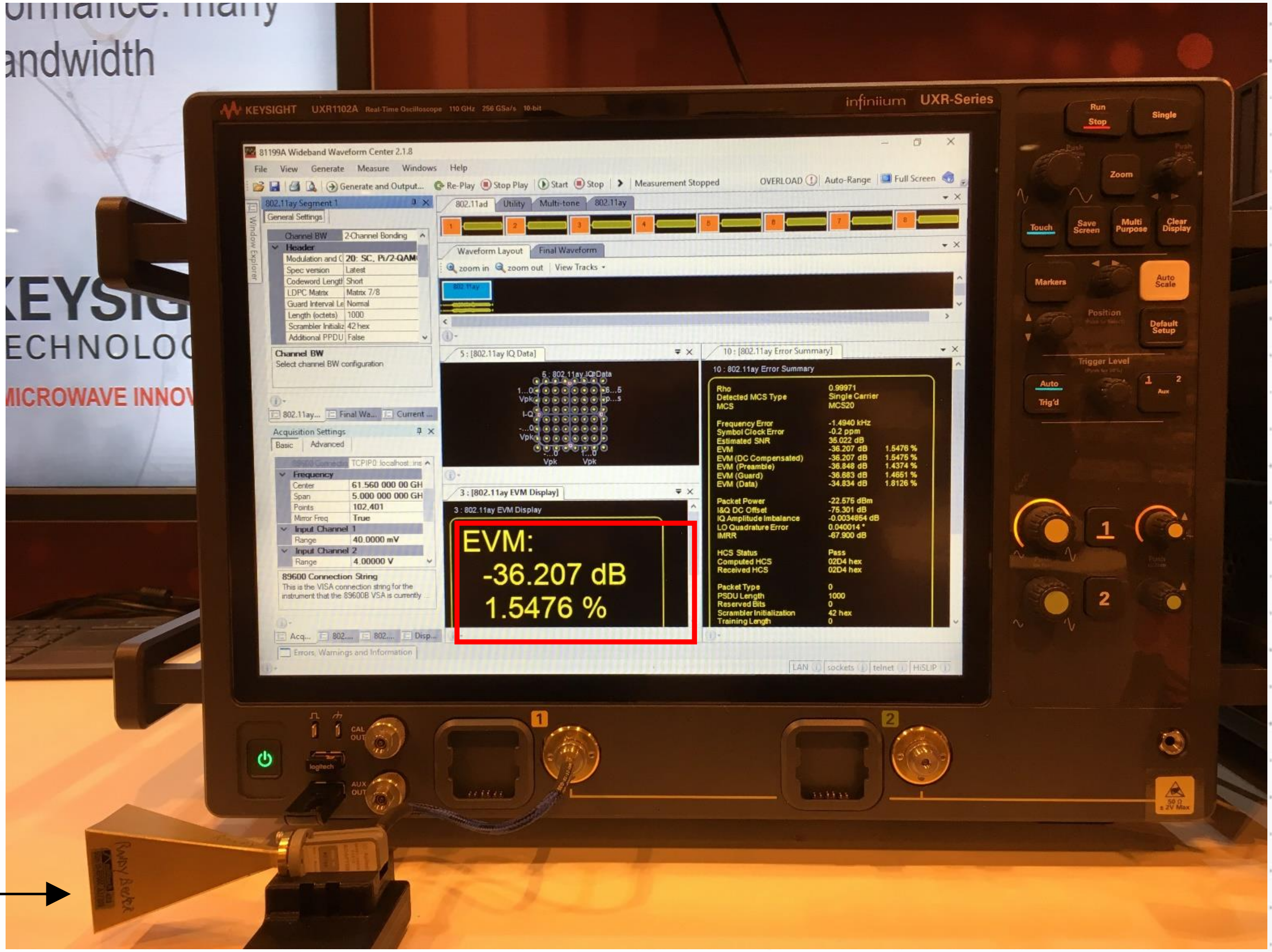
New: UXR for Wideband mmWave

ULTRA PERFORMANCE REAL-TIME 110 GHZ OSCILLOSCOPE

- Models from **13 GHz to 110 GHz** of real-time bandwidth
- 2 or 4 channels per scope - **ALL** with **FULL** rated bandwidth
- Best in class sample rates:
  - 13 – 33 GHz models: 128 GSa/s per channel
  - 40 – 110 GHz models: 256 GSa/s per channel
- 200 Mpts/ch standard – Upgradable to 2 Gpts per channel
- **High-Definition 10-bit Analog-to-Digital Converter (ADC)**
- Best signal integrity and vertical resolution
- **Hardware based acceleration ASICs**
- Optional self calibration module – enables you to perform a full factory quality calibration at your location

Direct Digitization and Demod of Wideband mmWave Signal

Close-Up of UXR Demod Measurement of 61.56 GHz Signal, 4.32 GHz BW



Signal Received into Horn Antenna. Input into Ch1 of UXR

Summary

- New wideband millimeter-wave R&D testbed offers flexibility and scalability
- Testbed was applied to 802.11ay as an example of an emerging millimeter-wave application
- Demonstrated performance achievable for 802.11ay
- New UXR and M8131A bring new breakthrough capability for wideband signal analysis

KEYSIGHT TECHNOLOGIES